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An Automatic Control Specialty
for the
Mechanical Engineering Department

D. L. Smith
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A 1982 NAVSEA review of the Naval Engineering (NE) curriculum identified the need for an increased emphasis on automatic controls specialty skills for NE graduates. This report describes a summer of research aimed at determining how the Mechanical Engineering Department can meet the NE automatic controls educational needs. An approach to improved coursework is identified and a supportive research program is discussed.

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1. Introduction

In the spring of 1982 a review of the Naval Engineering curriculum was held by the Naval Sea Systems Command (NAVSEA). A major finding of that review was that more emphasis needed to be placed on the automatic controls specialty skills within the curriculum, and especially on integrated propulsion control topics. The existing Educational Skill Requirements (ESR's) were rewritten and a new, required controls course was authorized. In order to meet the need, a new faculty member was recruited and the Mechanical Engineering (ME) Department was funded by NAVSEA to assist in developing the new controls course. The funding was used, in part, to sponsor a research intercessional period for the new faculty member, thus allowing him to determine an approach to meeting the Navy's requirements for teaching in the controls area at the Naval Postgraduate School (NPS). This report is a summary of the controls curriculum research which took place during the summer of 1984.

The incoming faculty member was observed to be somewhat out of touch with the mainstream of controls and in need of familiarization to the Navy approach to controls. This orientation problem was approached through a set of three, one-week, resident, state-of-the-art survey courses in controls taught by the Massachusettes Institute of Technology (MIT), interspersed with visits to Bath Iron Works and General Dynamics' Electric Boat Division. These five orientation milestones formed the core of the intercessional period and, when supported by interviews with key Navy personnel during the summer, form the basis for the recommendations which follow.

This report is organized into five sections: the present introductory section is followed by a section describing the summer background orientation; the third section deals with a course development approach; the fourth section discusses research recommendations; the final section contains a summary.

2. Background Orientation

The three MIT summer courses which were taken were: "Modern Methods for Nonlinear Control System Design", course 2.63s; "Computer-Aided Multivariable Control Systems Design", course 6.64s; and "Robot Manipulators, Computer Vision, and Automated Assembly", course 6.87s: The first two courses were selected since state-of-the-art Navy machine control problems (e.g. gas turbines, steam plants, diesel engines, and robotics) are known to be nonlinear as well as multivariable. The robotics course was added as a study in a high-interest controls application area.

The course on nonlinear control systems was developed by MIT to meet a major problem in controls that has been emerging over the last decade: a gap has been growing between "real world" control engineering needs and the existent, elegant theories for designing linear control systems. In theory, control system design is the direct application of well-established techniques; in reality, nonlinear effects can make control system design a costly and tedious exercise in cut-and-try engineering. Success has often been determined by the experience, intuition and good luck of the designer. However, major strides have been made in various fields of nonlinear systems theory which tend to alleviate this problem. In particular, this course concentrated on frequency-domain design and analysis methods and recent related research results. The course was formulated primarily for practically-oriented control systems engineers with special emphasis placed on techniques that are useful for industrial controls problems. Topics covered in the course included:

Fundamental properties of nonlinear systems

Simulation (deterministic and stochastic)

Functional analysis

Stability (Lyapunov, Popov, large scale systems)

Geometrical analysis methods

Controller design by factorization methods

Describing function methods (sinusoidal and random inputs)

Bifurcation theory

Identification of nonlinear systems

The nonlinear control course was organized and taught by Dr. J. Karl Hedrick of MIT and Dr. James Taylor of General Electric Co. There were 18 registrants who came from the U.S., Canada, and Mexico in addition to six auditing graduate students from MIT. The emphasis on frequency domain methods attracted a strong representation from the rotating machinery industrial community, especially Sundstrand, Pratt & Whitney, General Electric, and Borg-Warner. Also represented were Lawrence Livermore and Sandia National Labs and three major aircraft companies. Several of the participants characterized the course content as two or more academic quarters of material at the Masters or Ph.D. level condensed into a one week, 40 hour format. In discussing this with Dr. Hedrick, he expressed regret over not being able to cover other highly pertinent topics, such as optimal control and state-space methods, and he hoped to expand his course into these areas. This was not a shortfall in the curricular research however, as the course on multivariable systems nicely filled in the gaps.

The course on multivariable systems was developed to improve awareness of the advantages offered to control system designers by advances in microprocessors and VLSI technology. In particular, the course discussed methodology which can greatly improve the performance of a multivariable physical control system by dynamically coordinating several control variables to achieve good command tracking and disturbance rejection in several control channels simultaneously. The course material was an integration of time domain, state-space design methods (optimal control) with frequency domain performance requirements of the sort which are common in design specification.

The following topics were discussed:

Fundamentals of multivariable feedback design

Modeling in the time and frequency domains

Stability and Robustness

Overview of multivariable design philosophies

Model based compensators

Linear quadratic designs

Kalman filter designs

Loop transfer recovery

Research directions

The multivariable controls course was organized and taught by Dr. Michael Athans of MIT. There were 40 registrants from the U.S., Switzerland, Israel, Italy, and West Germany. Seven universities were represented including Johns Hopkins, Rhode Island, New Mexico State, and Maine. Again, there were perhaps six MIT graduate students auditing the course. Most of the registrants came from a cross-section of top U.S. companies: IBM, General Electric, General Dynamics, and General Motors to name a few. The Army, NASA, and the Air Force were represented. Once again, the course content was almost two quarters at the masters or Ph.D. level condensed to one 40-hour week.

The relative course attendance at the two controls courses (40 vs 18) reflects the present general predominance of multivariable (time domain) controller design methods. Nevertheless, frequency domain analysis techniques are often used as design validation tools. In discussing this with Dr. Athans, he mentioned the recent case of the Pratt & Whitney F-100 gas turbine controller design for aircraft application. Here, the design requirements were given in the time domain, the design was developed in the time domain using the methods discussed in his course, and the design was validated in the time domain.

The course on robotics was developed to prepare participants to make sound decisions in the acquisition and application of existing hardware and future systems. The emphasis in the course was on developing strategies for the solution of problems in sensing, spatial reasoning, and manipulation. A great deal of time was spent on computer vision and reasoning, with relatively little on manipulation and control.

Topics that were covered:

Robot Manipulator Kinematics

Robot Manipulator Dynamics

Robot Manipulator Control

Grippers and Tools

Robot Programming

Image Formation

Object Recognition

Robot Applications

Systems Components

The robotics course was organized and taught by Dr. John Hollerbach, Dr. Michael Brady, Dr. Thomas Lozdro-Perez, and Dr. Bert Horn of the MIT Artificial Intelligence Lab. There were 57 registrants representing 34 major companies (e.g. GM, GE, IBM and Ford Motor Co.) and 10 universities (Missouri, Ohio State, Case Western and McGill). There were approximately 10 MIT graduate students attending the lectures and workshops. The schedule was again highly compressed but, from a mechanical engineering viewpoint, somewhat disappointing. The brief treatment of manipulation and control was very useful, but the emphasis on machine reasoning seemed to have no purpose. The advantages of various hardware alternatives were not discussed, nor was systems synthesis discussed. Consequently, the participants were left somewhat ill at ease with the course content. The apparent consensus was that the course failed to meet its first objective: participants were not prepared to make sound decisions in the acquisition and application of existing hardware and future systems. They were however, given a good understanding of the state-of-the-art in robot vision, machine reasoning, and gripping problems.

A one-day visit to General Dynamics' Electric Boat Division at Groton, Connecticut, was scheduled to gain familiarity with subsurface fleet control design and construction. A tour of a nearly complete Trident was conducted by Mr. Pete Petrides of the System Technology Group, and the maneuvering control system was discussed at some length during and after the tour. The innovatioons in Trident control design were discussed, especially the time sharing of on-board computer facilities to accomplish controls tasks. Possible thesis topics were discussed.

A one-day visit to Bath Iron Works was also scheduled. The visit included a tour of nearly complete FFG-7 and a briefing by Mr. Jan Erickson, a production facility manager. The briefing focused on controls and automation in the manufacturing process. Bath is just now beginning to look at applications of robotics, and they do already have some hard automation in their plate cutting processes. In fact, their plate cutting process may be called "true" CAD/CAM in that the design is first created by engineers using computer aided design methods, it is then transferred to a data base by computer-aided drafting, and is finally manufactured by a computer driven manufacturing system which accesses the data base. The staged-design, modular ship construction approach used at Bath was explained in some detail in describing the whole-ship manufacturing process. Problems in manufacturing accuracy control were discussed as possible research topics.

A variety of interviews were scheduled during the course of the summer. The purpose of the interviews was to meet key Navy personnel, to discuss their views on NPS educational needs in the controls area, and to discuss possible mutually beneficial research opportunities. In view of the informal nature of the interviews, specific quotes and references do not seem appropriate. Nevertheless, the concepts and philosophies which were discussed have been incorporated in the following material to the maximum extent possible. The following personnel were interviewed:

CAPT George Lachance	- NAVSEA, Director, Machinery Group
Mr. William Kastner	- NAVSEA, Assistant for ED Plans and Policies
CAPT Corky Graham	- MIT Programs, Commanding Officer
Mr. Dale Danielian	- NAVSEA, Ship Design and Engineering
Dr. Alan Meyrowitz	- ONR, Engineering Sciences
CDR Rich Spanholtz	- SUPSHIP Bath, Executive Officer
LCDR Bart Everett	- NAVSEA, Assistant for Robotics
Mr. Pete Petrides	- General Dynamics Electric Boat Division, Systems Technology Group

The importance of modeling and simulation can scarcely be overemphasized in controls coursework. In order to identify this type of source material for course development, Dr. Joe Rubis of Propulsion Dynamics, Inc. and Dr. Martin Abkowitz of MIT were visited. Each of these gentlemen is a recognized authority in the area of ship and/or propulsion modeling, and both have agreed to participate in the development of an NPS ME controls course. Dr. Rubis has been approached about presenting two weeks of lectures as part of ME 4802, Marine Propulsion Control; Dr. Abkowitz will be presenting one week of lectures as part of ME 4215, Dynamics of Marine Vehicles. The integration of this material into a "controls" course sequence will be addressed in the following section.

3. Course Development Approach

Automatic controls is widely recognized as a fundamental area of instruction in mechanical engineering, with courses typically offered at both the undergraduate and graduate levels. A sample program would find one, required introductory course in linear control theory offered at the undergraduate (senior) level. Optional follow-on courses in modern control theory are usually offered at the senior or graduate level. The present ME course development problem is thus one of identifying an ME controls program for NPS which first meets the Naval Engineering curricular needs and second is consistent with a widespread controls teaching practice. In solving this problem, it is important that both required and elective course content be identified and a supportive thesis and faculty research program be initiated. This section of the report deals with identifying the teaching needs of such a program and recommending an approach to meeting those needs.

All Naval Engineering (NE) students need to be conversant with the way in which shipboard control systems work. They need more than an introductory level of knowledge, they need to know the why and how of actual controller operation. In fact, one of the lessons learned during the DDG51 design process was the need to prepare the blue-suit Navy for a fast-paced proposal evaluation process by education beforehand in modern automatic controls. This observation is endorsed in an existing Educational Skill Requirement which calls for training in integrated propulsion control systems. The course development approach must identify the course(s) required to prepare a student for understanding integrated propulsion control. The present approach is to offer two required courses to the NE students. The first course, EE3413, Fundamentals of Automatic Control, is a course designed for, and required of, NE students only. It is comparable to the undergraduate introductory controls courses offered in other universities. The second, ME 4802, Marine Propulsion Control, is intended to teach the follow-on controls theory which leads to an understanding of integrated propulsion control. The difficulty with this approach is that ME 4802 objectives must become ill-defined and overly ambitious in view of the requirement for integrated propulsion control.

Integrated propulsion control is a broad, hardware-oriented control concept which is continually evolving. This type of control is "integrated" in the sense that all propulsion control signals are derived from a single power lever on a propulsion control console. For the DD963 and FFG-7 classes of ships, it was achieved through a collection of ad hoc controller design methods centered around computer-aided data processing. For the newer classes of ships (e.g. DDG51) a move was made toward implementation of a modern controller design. Other implementations exist for various propulsion units.

Clearly, several types of design must be taught to form a basis for understanding integrated propulsion control as commonly found in the fleet. Thus, the ESR which requires teaching of integrated propulsion control systems is, in reality, an ill-defined and ambitious requirement.

The NPS approach to education should be to educate in the basic principles and to illustrate those principles through the study of timely and representative systems, preferably naval systems. Similarly, ME coursework should educate in the basics of control theory, and illustrate those principles through the study of integrated propulsion control systems (and perhaps other control systems as well). The details of ship-to-ship variations should be properly reserved for Engineering Officer of the Watch Certification training.

A second course in controls is necessary at NPS since the first course gives little practical understanding of modern control systems. There are so many introductory concepts to cover that a practical level of knowledge cannot be reached in one quarter. A second controls course at most universities begins to cover modern control theory, which is the basis for modern control implementation. This is usually an optional theory course at the senior or graduate level intended for those students who desire to achieve some specialization in controls. However, a second required course in controls at NPS should present modern control concepts without forcing all NE students to become modern control specialists. Consequently, some blend of introductory-level modern control theory, with hardware implementation case studies, seems to be a worhwhile approach to the NPS second course.

A system view of the hardware can form the basis for covering all necessary controls teaching topics, whether they are required or optional. In the discussion which follows, the propulsion system is analyzed to identify necessary teaching topics. The propulsion system is first subdivided into the power subsystem and the control subsystem. The two subsystems can be further divided into six groupings as shown in Figure 1. The six propulsion groupings, in turn, are examined to identify those topics which need to be taught in order to achieve an understanding of the assembled, controlled system. Notice that this approach is fundamental since all propulsion systems are composed of the same groupings.

PROPULSION SYSTEM

POWER SUBSYSTEM	CONTROL SUBSYSTEM
1. Propulsors	4. Sensors
2. Power Transmissions Elements	5. Controllers
3. Load considerations	6. Control Power Elements

Figure 1. The Propulsion System

The controls teaching topics are shown in Table 1. The table shows the courses which presently cover the topics, and whether they are elective (E) or required (R). The table also shows a series of proposed courses which fully cover the necessary material. In total, the topics have been identified with the goal of producing a student who can be reasonably identified as a potential ME specialist in automatic controls with a logical departure point for thesis work in controls.

TABLE 1. Propulsion Controls Topics and Coursework

(R) required, (E) elective

Power Subsystem	Present	Proposed
1. Propulsors		
Overview	ME 4802 (R)	ME 3802 (R)
Steady-State Modeling	ME 3240 (R)	ME 3240 (R)
Dynamic Modeling	----	ME 3802 (R)
Hands-on-Lab	ME 3241 (R)	ME 3241/ME 3802
2. Power Transmission Elements		
Overview	ME 4802 (R)	ME 3802 (R)
Steady-State Modeling	ME 3711 (R)	ME 3711 (R)
Dynamic Modeling	----	ME 3802 (R)
3. Load Considerations		
Overview-performance Rqmts	ME 4802 (R)	ME 3802 (R)
Steady-State Modeling	ME 3240 (R)	ME 3240 (R)
Dynamic Modeling	----	ME 3802 (R)
Control Subsystem		
4. Sensors		
Overview	ME 4802 (R)	ME 3802 (R)
Characteristic Performance	ME 2410 (R)	ME 2410 (R)
Hands-on-Lab	ME 2410 (R)	ME 2410/ME 4803
5. Controllers		
Overview	ME 4802 (R)	ME 3802 (R)
Control Logic Overview	ME 4802 (R)	ME 3802 (R)
Characteristic Performance	----	ME 3802 (R)
Hands-on-Lab	----	ME 3802 (R)
6. Control Power Elements		
Overview	ME 4802 (R)	ME 3802 (R)
Fluid Power performance	ME 4801 (E)	ME 4801 (E)
Electrical Power performance	----	ME 4801 (E)
Hands-on-Lab	----	ME 4801 (E)
Power Subsystem Analysis		
Overview	ME 4802 (R)	ME 3802 (R)
System Identification	----	NE 4803 (E)
Control Subsystem Synthesis		
Overview	ME 4802 (R)	ME 3802 (R)
Design Specs and Rqmts	ME 4802 (R)	ME 3802/ME 4803
Control Options	----	ME 4803 (E)
Controller Logic Design	----	ME 4803 (E)
Microprocessor Circuit Design	----	ME 4803 (E)
Hands-on-Lab	----	ME 4803 (E)

The present approach to teaching controls is very weak in lab work and in dynamic system modeling. The introductory course in automatic control (EE3413) is taught by the EE Department for NE's only. The second course, ME 4802, Marine Propulsion Control, has become a very general course and, since it is required, it eliminates a 4000 level elective slot in the NE curriculum. The sequence badly needs a 3000 level required controls course to form the basis for ME 4000 level electives and specialization. In fact, the material which is taught in ME 4802 is arguably 3000 level material and does not justify a specialization course (4000 level), nor should it be such. Additionally, there is no required lab work on dynamic systems anywhere in the curriculum. A hands-on lab is now being developed as part of ME 4801, but students should have introductory lab work at the system level (ME 4802). Furthermore, there is little, if any, required coursework in dynamic systems modeling anywhere in the curriculum.

The proposed approach to controls coursework calls for a more agressive ME involvement. The introductory course (EE 3413) should be taught by the ME Department (as, say, ME 3801). Since this is an introductory level course, all ME faculty (at least those in design) should be able to teach it. This would also lighten the teaching burdens of the EE Department. The second required course (presently ME 4802) would be appropriately offered as ME 3802, Marine Propulsion Control. This course would be essentially the same as ME 4802 as presently taught, with the important addition of a hands-on controller Lab. Students would be given an overview of "real world" controlled systems from which they can identify their specialization needs and desires. Plans are now being formulated to introduce students to propulsion control and robotics controllers in hands-on labs. Integrated propulsion control can be taught as a system case study in ME 3802, as it now is in ME 4802, in order to satisfy the existing ESR.

The present and proposed course sequences are shown in Figure 2. Note that the ME 3802 course (presently ME 4802) has a key overview role; it should also be a required course as it places the student and advisor in a position to evaluate the potential and desire to continue on in controls and it provides the student with very useful propulsion control knowledge in the process. Furthermore, since the controls courses are fundamental in nature, they should be taken early enough in the MSME program to permit follow-on courses to be taken before thesis work is begun, if so desired. The courses shown are those which would be taught by the ME Department; further specialization coursework would be available through the EE Department. Teaching content for electric actuators, the controller lab, and microprocessor circuits should be developed in conjunction with the EE Department as condensed versions of these topics are seen as necessary to give the ME student the proper scope for control systems understanding.

PRESENT SEQUENCE

Required	Prerequisites
EE 3413 Fundamentals of Automatic Control	none
ME 4802 Marine Propulsion Control Systems	EE 3413
Electives	
ME 4801 Fluid Power Control	EE 3413
ME 4902 Robotics Reading Course	consent of instructor

PROPOSED SEQUENCE

Required	Prerequisites
ME 3801 Introduction to Automatic Control	ME 2502
ME 3802 Marine Propulsion Control	ME 3801
Electives	
ME 4801 Power Control Elements	ME 3802
ME 4803 Control System Synthesis	ME 3802, ME 4801
ME 4902 Robotics/Controls Reading Course	consent of instructor

Figure 2. Automatic Controls Coursework in Mechanical Engineering

4. Research Recommendations

Two areas of research in automatic control now appear to be appropriate for the ME Department at NPS: marine propulsion control and robotics. NPS ME students are expressing a high level of interest in both topics, as is the Navy in general. Part of the summer's activity was invested in an examination of these frontiers in an effort to identify viable ME topics for thesis and faculty research.

Marine propulsion control offers many topics for useful research, among them are: hardware and computer simulation; design and implementation of controllers; and research into wear of control components. The characterization of various propulsion plant components with mathematical models will be a fruitful source of thesis topics. Gas turbine models, seaway models, and propeller/load models are all necessary to confidently validate controller designs before hardware is assembled. Computer simulations can be used to study sensor loss accomodation, disturbance and parameter sensitivities, voting logic, worst case scenarios, and the process of control development. Hardware simulations and/or controller prototypes can be useful in teaching situations and may lend insight to follow-on advanced controller research. The characterization of wear will enable the prediction of evolutionary performance, and can help to minimize problems in control overdesign or underdesign.

Robotics research is a very fast moving frontier at the present; many universities and government labs are just starting to organize large scale research. LCDR Bart Everett (SEA90G) has been tasked with coordinating the Navy's robotics efforts from the position of Special Assistant for Robotics to VADM Fowler of the Naval Sea Systems Command. Part of this effort is currently aimed at coordinating a program element for the 1987 POM in the area of non-industrial-research. LCDR Everett arranged several meetings with NAVSEA, NSWC, and ONR personnel to discuss possible research topics for ME students and faculty. Some of the topics discussed were:

Robotic welding (NAVSEA sponsor)

weld characterization and sensors
monitoring
controls
prototyping

Robotic At-Sea Repair (NAVSEA sponsor)

feasibility evaluations from simulations
conceptual studies
prototyping

Heavy Lift Robotics (ONR or NSWC sponsor)

design
simulation
prototyping

An ME research proposal entitled "Optimal Control of Robotic Mechanisms" has been recently funded by the NPS research foundation. The proposal will allow the ME Department to purchase a small table-top robot manipulator arm and a controller for the study of control strategies, especially control for heavy-lift. These devices will increase the hands-on awareness of faculty and students alike, but they are just a beginning in this area. Every effort should be made to obtain an industrial quality robotic manufacturing system at the earliest opportunity. Student and Navy interest in this area is quite high and the educational and research opportunities would be numerous, not only in the controls area, but in other areas as well (e.g., design of grippers and end effectors, actuation, stress and strain analyses, CAD/CAM methods, etc.).

5. Summary

Much of modern control theory is too advanced for the average ME (NE) student; however, the average ME student does not need to become an expert in modern control theory. The students should be required to be conversant in modern shipboard control systems. A course sequence has been proposed which contains two required courses which are similar to the present two required courses, they are designed to introduce modern control topics in such a way that is appropriate to a course required of all NE students. Course content and timing are critical to an effective curriculum. The fundamental nature of automatic control suggests that these courses be taken early in the program (say, as ME 3801 and ME 3802) rather than late in the program as is presently done (ME 4802). Further specialization can be achieved through 4000 level electives which have been presented and discussed. Research topics have been presented and discussed in the Navy high-interest areas of marine propulsion control and robotics. These topics should be pursued through thesis research and proposal activity.

The summer orientation to the mainstream of controls and the Navy way of doing things was essential for the new faculty member. The wide separation between modern control design as taught by MIT and the recently fielded control systems found in the surface Navy is confusing. The professor needs to prepare the students to meet this technology gap without digressing into ad hoc designs and case by case exceptions. We need to educate in the basics and leave room for specific on-the-job training. Nevertheless, the awareness of the controls technology gap inevitably leads to a more worthwhile approach to teaching and research which, in turn, benefits the Navy. The author is grateful for the opportunity provided and would encourage similar programs for other new faculty.

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